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Performance assessment of a combined foundation system of end-bearing and floating piles in a challenging soil profile

Évaluation des performances d'un système de fondation combiné de pieux porteurs et de pieux flottants dans un profil de sol complexe

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ABSTRACT: This study evaluates the performance of a combined foundation system of end-bearing and floating piles in a challenging soil profile consisting of a sand layer of thickness of 12 m overlying a substantial deposit of soft to medium stiff clay in Egypt Nile Delta deposits. The objective is to assess the effectiveness of this foundation system in providing stability highlighting the load-sharing ratios. This system offers a time-efficient alternative to conventional soil improvement techniques such as wick drains or vacuum consolidation. These methods often require considerable time and may have limited effectiveness on deep clay soil, especially beyond a depth of 10 - 15 meters below ground level, hence the challenge arises. By incorporating piles of varying lengths, this system provides a rapid solution for achieving the desired stress distribution by capitalizing on the high end-bearing capacity in sand and the skin friction provided by long piles in clay. 3D numerical simulations were conducted to assess the performance of three systems, using only end-bearing piles, only friction piles, and the combined foundation system. The insights gained assured that this system has a superior performance on decreasing settlement and benefiting from all factors, piles end bearing in sand, high friction from piles rested in clay, and bearing capacity of soil beneath the raft.

RÉSUMÉ: Cette étude évalue les performances d'un système de fondation combiné de pieux en bout et flottants dans un profil de sol difficile, composé d'une couche de sable d'une épaisseur de 12 m recouvrant un dépôt substantiel d'argile molle à moyennement raide dans les dépôts du delta du Nil en Égypte. L'objectif est d'évaluer l'efficacité de ce système de fondation dans la fourniture de stabilité, en mettant en évidence les ratios de partage de charge. Ce système offre une alternative efficace en termes de temps aux techniques conventionnelles d'amélioration des sols telles que les drains de mèche ou la consolidation sous vide. Ces méthodes nécessitent souvent un temps considérable et peuvent avoir une efficacité limitée sur les sols argileux profonds, en particulier au-delà d'une profondeur de 10 à 15 mètres sous le niveau du sol, d'où le défi. En incorporant des pieux de longueurs variables, ce système fournit une solution rapide pour atteindre la distribution de contraintes souhaitée en capitalisant sur la capacité portante élevée en bout dans le sable et la friction de la peau fournie par les pieux longs dans l'argile. Des simulations numériques 3D ont été réalisées pour évaluer les performances de trois systèmes, en utilisant uniquement des pieux en bout, uniquement des pieux de friction et le système de fondation combiné. Les informations obtenues ont confirmé que ce système offre des performances supérieures en termes de réduction des tassements et bénéficie de tous les facteurs, la capacité portante des pieux en bout dans le sable, la friction élevée des pieux reposant dans l'argile et la capacité portante du sol sous la dalle.

Keywords: Piled raft foundations; challenging soil profile; numerical simulations; load-sharing ratios; floating piles.

1 INTRODUCTION

The utilization of piled rafts (PRs) for the construction of high-rise buildings and offshore structures has proven to be an effective and cost-efficient solution for controlling total and differential settlements and increasing bearing capacities. Traditional design approaches often adopt the assumption that all structural loads are supported by piles, neglecting the significant load-sharing potential of soil beneath the raft, depending on the pile group concept. However, remarkable research, e.g., by Cooke (1986) has emphasized that about 30% of the total load can be effectively supported by the soil. Furthermore, Katzenbach, et al. (1998) pointed out the importance of taking the soil-structure interactions between raft, soil, and piles while designing a PR. Hence, the design approaches for PRs, which consider this load-sharing effect, are more rational and economical. Over the past decades, researchers have studied the behavior of PRs using various techniques for different soil types. Experimental studies have been conducted to understand the PRs behavior in sandy soils, for instance, by Elwakil and Azzam (2016) and in saturated clay such as Hoang et al. (2024), and Hoang and Matsumoto (2020). Numerical methods have been employed to investigate PR behavior in stiff clay, e.g., Mali and Singh (2018). It is worth noting that the suitability of PRs can differ depending on geological soil profiles. Poulos (2001) pointed out that in situations with end-bearing piles and a layer of loose sand or soft clay near the foundation surface, PRs may not be the best choice because of the limited contribution of the soil after losing contact due to several factors. Reul and Randolph (2003) analyzed PRs in over-consolidated clay. Furthermore, the application of PRs extends to various soil types, as evidenced by studies in Frankfurt stiff clay (Sommer, et al. 1985) and Berlin Sand (El-Mossallamy, et al. 2006). Researchers have explored the behavior of PRs in soft clay as well, such as studies conducted by El Sawwaf et al. (2022a, 2022b) who proved the applicability of PRs in soft clay, under reasonable stress, emphasizing the ability of soil to carry a substantial portion of the load conditional on the shaft resistance of the piles.

1.1 Research objectives and methodology

In areas of the Egypt Nile Delta with a soil profile featuring a sand layer overlying soft to medium stiff clay, traditional ground improvement techniques like vertical drains and vacuum consolidation may not be effective due to the limited efficacy of the upper fill on the clay and the time required for these methods. Therefore, this study proposes a piled raft (PR) solution. End-bearing piles, where all tips are in sand, may not be optimal due to limited friction from short lengths and the decreased end bearing because of soft layers beneath while using long piles, where all tips are in soft to medium stiff clay, sacrifices end-bearing. To address these challenges, numerical simulations will be conducted to evaluate three scenarios: Short piles with all tips in sand (end-bearing piles), long piles with all tips in clay (friction piles), and mixed configurations combining end-bearing and friction piles. Through these simulations, the research aims to provide insights into cost-effective foundation solutions for structures in challenging soil profiles like those found in the Egypt Nile Delta.

2 SOIL PROFILE DESCRIPTION

This study was carried out on an actual soil profile situated within the Nile Delta deposits of Egypt. The soil profile consists of a 12-meter layer of medium to dense sand, which is underlain by an extensive 48-meter layer of soft to medium stiff clay. Beneath this clay layer, a further layer of dense sand extends to the end of the boreholes. The groundwater level is situated at a depth of approximately 3.0 meters below the ground level. The site investigation was conducted by Hamza Associates, a reputable organization in Egypt, with expertise in geotechnical studies.

3 FINITE ELEMENT MODELING

The foundation was subjected to a uniform load (q) of 150 kPa (the raft own weight and additional stress). The constitutive model, mesh, boundary conditions and piles and raft modelling are presented in the following subsections.

3.1 Constitutive model

In this study, the Hardening Soil (HS) model was adopted for all soils, as the (HS) model can simulate the behavior of both stiff and soft clays (Schanz, 1998). In addition, Brinkgreve et al. (2010) reported that the HS model covers the behavior of a wide range of sands. A distinctive attribute of the HS model is its ability to account for stress path and their consequent impact on soil behavior. It considers three stiffnesses, the secant stiffness (E_{50}^{ref}), Oedometer loading stiffness, (E_{oed}^{ref}), and unloading/reloading stiffness, (E_{ur}^{ref}). Furthermore, this model considers the stress-dependency of stiffness.

3.2 Finite element mesh and boundary conditions

The parametric investigation was executed on a quarter-section of the PR, chosen for its symmetry. The lateral limits of the soil domain were restricted to prevent horizontal translation while permitting vertical soil displacement. The horizontal boundary was 4 times of raft width from the raft edge. The vertical soil boundary was set to exceed three times the width of the raft below the equivalent raft depth, as per the equivalent raft concept proposed by Tomlinson (2001) for the case with the longest piles. The model employed a medium-mesh size, although a finer mesh was utilized within the active zone.

3.3 Modelling of raft and piles

The raft was modeled using a 10-node tetrahedral element, while the piles were modeled as 3-noded embedded beam elements with fixed head conditions. The study also considered the interaction between the soil and the structural elements, incorporating an interface strength value of 0.7 for the concrete-soil interface, Elwakil and Azzam (2016). Bored piles were utilized in the study, with layer-dependent pile friction activated. The end-bearing value of the piles was not limited, allowing it to be obtained from the program solution.

3.4 Construction stages

The analysis included 5 stages, shown in Figure 1, the initial stage, excavation up to the depth of 2.0m, pile installation, raft construction, and loading. The excavation was carried out with appropriate slopes to prevent side falling. The displacement was set to be zero after the pile installation stage, where the raft settlement was the summation of the raft construction and loading stages. Tables (1-3) show the input parameters.

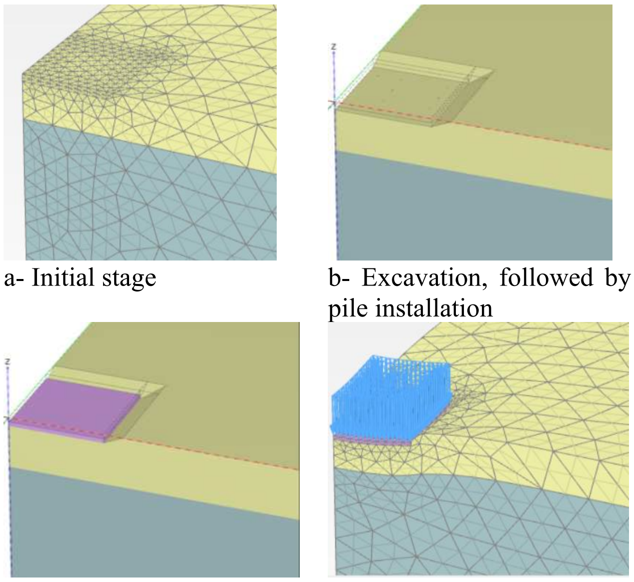

Figure 1. Stages of construction.

Table 1. Parameters of soft to medium clay layer.

Parameter	Soft to medium stiff clay
Elevation, below ground level (m)	12 – 60
Drainage type	Undrained (A)
Saturated unit weight (kN/$\mathbf{m^3}$)	17.50
$\mathbf{E_{50}^{ref}}$ (MPa)	8
$\mathbf{E_{oed}^{ref}}$ (MPa)	8
$\mathbf{E_{ur}^{ref}}$ (MPa)	24
Reference pressure, Pref (kPa)	100
Drained cohesion intercept, c' (kPa)	1
Drained friction angle, ϕ' (°)	26

Table 2. Parameters of sand layers.

Parameter	Upper Sand	Lower Sand
Elevation (m)	0 – 12	60 – 80
Drainage type	Drained	Drained
Unit weight (kN/$\mathbf{m^3}$)	18.0	19.0
$\mathbf{E_{50}^{ref}}$ (MPa)	45	60
$\mathbf{E_{oed}^{ref}}$ (MPa)	45	60
$\mathbf{E_{ur}^{ref}}$ (MPa)	135	180
Drained friction angle, ϕ' (°)	36	38
Dilatancy angle, Ψ' (°)	6	8

Table 3. Parameters of raft and piles.

Parameter	Raft	Pile
Model	Linear elastic	-
Unit weight (kN/$\mathbf{m^3}$)	25	24
Elastic modulus, E (MPa)	2.2×10^4	2.0×10^4

3.5 Parametric study

The vertical settlement and load sharing ratio (LSR), load carried by piles, were obtained for all cases where the raft was (40 × 40 × 1) m, and pile number (n), pile diameter (d), and pile spacing (s) were 64, 0.80 m, 6d, respectively. To study the effect of increasing pile length for the case of end-bearing piles, simulations were carried out on a PR with piles of 5, 6, 7, 8, and 9m. These lengths were changed to 20, 25, 30, and 35m in case of friction piles. Appropriate lengths of end-bearing piles, and friction piles would be selected to create the combined foundation system of end-bearing and friction piles. Figure 2 presents the different configurations studied of the combined foundation system.

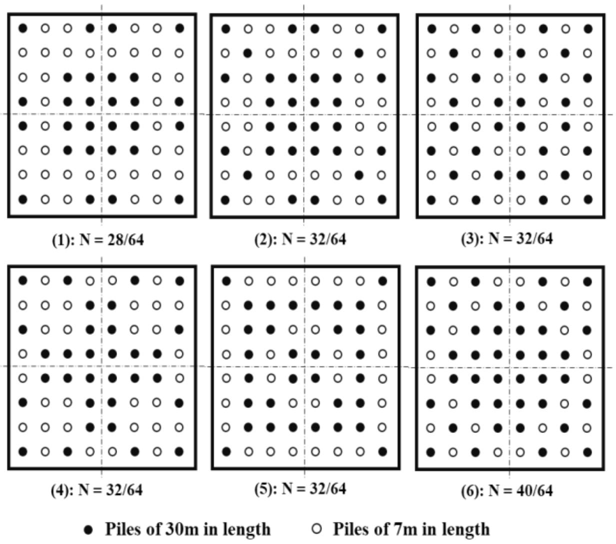

Figure 2. Different configurations of the combined foundation system of end-bearing and friction piles.

4 RESULTS AND DISCUSSIONS

A detailed analysis of findings, organized into three distinct categories is presented as follows:

1- using only end-bearing piles, 2- using only friction piles, and 3- using the combined foundation of end-bearing and friction piles.

4.1 Using only end bearing piles

As depicted in Figure 3, the various lengths of end-bearing piles consistently exhibited similar behavior even with increasing pile length. This may be explained as the longer pile length could affect the soft to medium stiff clay layer, as it brought the pile tips closer to this layer, resulting in higher load transmission through the end bearing. Regarding load sharing, it was observed that the total pile loads exhibited a gradual increase as the pile length increased up to 7.0 meters, (see Figure 4). Beyond this point, the rate of increase became limited. This can be attributed to the following: given that the skin friction of the piles increased marginally, the primary factor influencing load sharing was the end bearing; it was determined that pile lengths exceeding 7.0 meters were impacted by the presence of a weaker layer, soft to medium clay, as the depth beneath the pile tips was insufficient to achieve a higher end bearing capacity.

4.2 Using only friction piles

The primary aim was to evaluate how floating piles could effectively mitigate settlement in such a challenging soil profile. As illustrated in Figure 5, there was a notable reduction in vertical settlement as the length of the floating piles increased. This superior performance of floating piles compared to end-bearing piles could be the result of the substantial lengths, which provided a greater capacity for generating frictional resistance against movement. Additionally, under the same applied stress, the pressure bulb resulting in the case of long piles (friction piles) had a greater depth compared to that resulting in the case of short piles (end-bearing piles), (see Figure 6). Therefore, the settlement was smaller, as the stress was distributed over a larger volume of soil, causing less compression of soil particles. Regarding load sharing, Figure 7 illustrates the relationship between pile length and load sharing ratio. It was observed that the total pile loads exhibited a gradual increase with increasing pile length because of increasing pile friction. This increase was expected with increasing lengths; however, it can be linked to the increased vertical stress resulting from the own weight and external loads, leading to heightened horizontal stresses and consequently, an enhancement in frictional resistance.

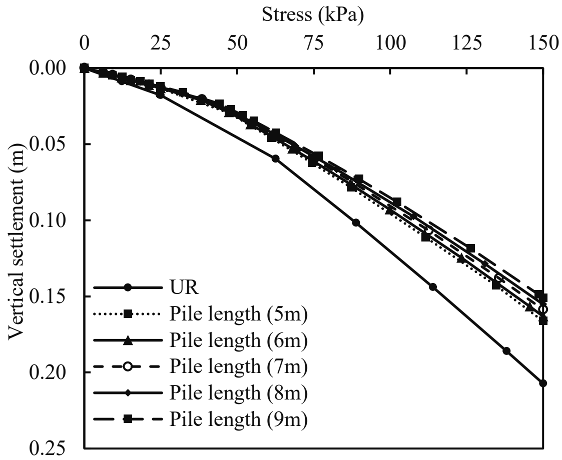

Figure 3. Relationship between stress and vertical settlement for UR and PR with all tips in sand.

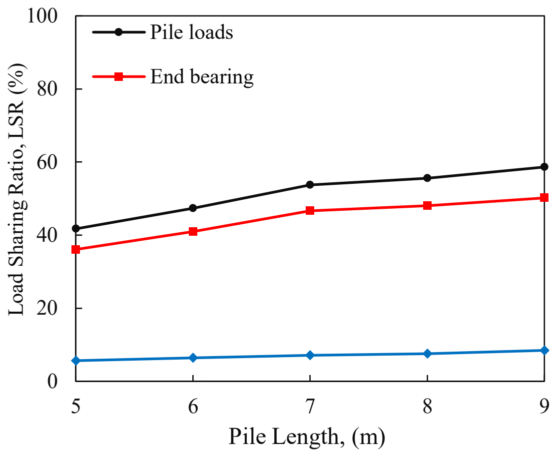

Figure 4. Relationship between pile length and load sharing ratio (LSR) for piled rafts with all tips in sand.

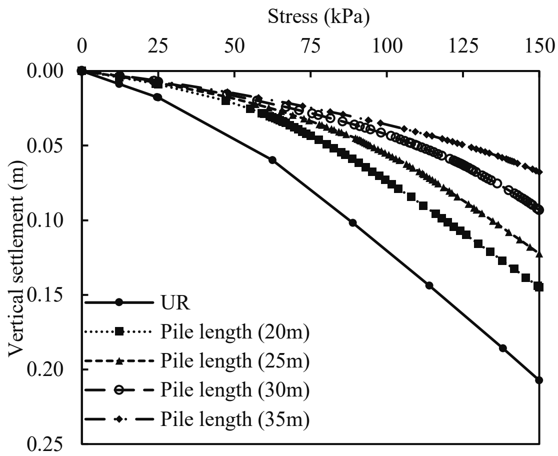

Figure 5. Relationship between stress and vertical settlement for UR and PR with all tips in clay.

4.3 Using a combined system of end bearing and friction piles

For this system, the lengths of 7.0m, and 30m were chosen for end-bearing piles, and friction piles, respectively. The length of 7.0 m for end-bearing piles was proven to be the most appropriate one, whereas the length of 30m for friction piles was chosen from an economic perspective. The relation between the applied stress and vertical settlement for the different configurations is presented in Figure 8. Mainly, the combined foundation system could achieve a decrease in the vertical settlement more than the chosen case from cases of end-bearing piles only. However, this system couldn't achieve the same decrease in settlement of the case of only friction piles, it may be adoptable based on the project criteria and requirements. The decrease in settlement was a result of benefiting from the frictional resistance of long piles and high-end bearing from short piles. Moreover, this system expanded the pressure bulb more than in all cases of end-bearing piles only (not presented due to space limitations), so the settlement of individual particles was reduced. To go deeper among the mixed systems, system 3 exhibited comparatively lower efficiency due to the random configuration of long piles, particularly away from the raft center. Conversely, system 6 was the most efficient choice, due to the higher number of piles. The performance of this system in decreasing settlement was nearly 90% of the friction piles system with 40 long piles and 24 short piles. The economic benefit was not using 552 m of concrete (around 278 m^3 of concrete). Therefore, employing this system can be a safe and economical solution. For the mixed systems 1, 2, 4, and 5, their stress-settlement behavior displayed similarities. This superiority of system 1 even with less number of piles was attributed to its strategically concentrated pile positioning around the center of the raft, coinciding with the location of maximum vertical settlement. For the load sharing, Table 4 shows that the piles carried around half of the total load in all cases, which was around 30% carried by frictional resistance. This assured the importance of growing friction in deeper soil that was influenced by the increase in horizontal stresses.

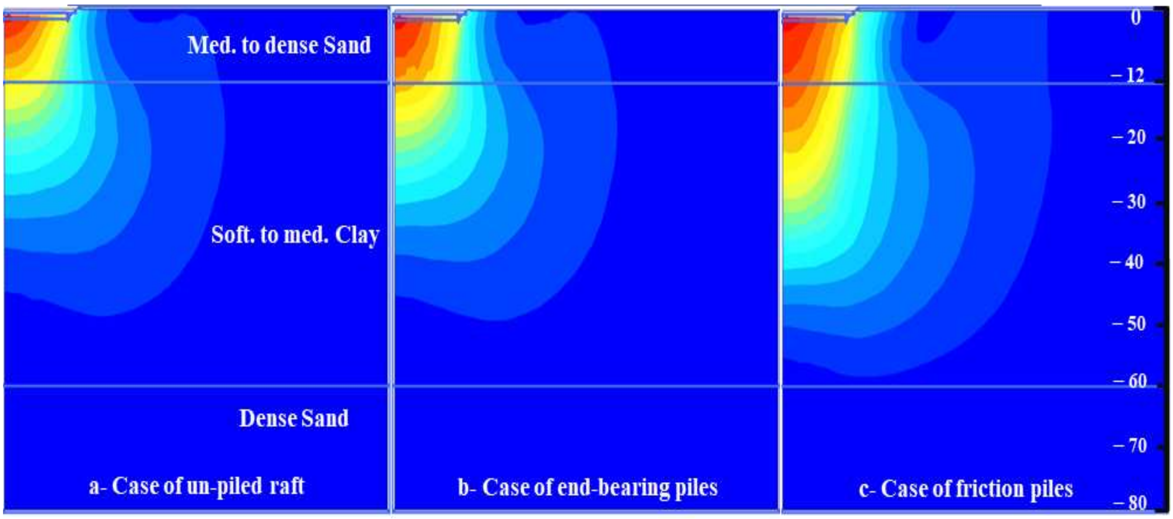

Figure 6. Stress distribution for different cases (a- un-piled raft; b- case of end-bearing piles; case of friction piles).

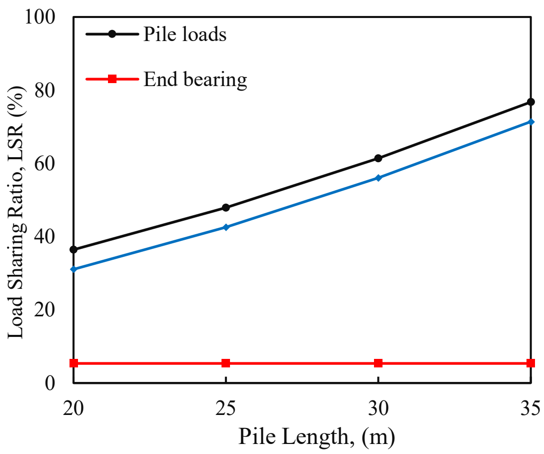

Figure 7. Relationship between pile length and load sharing ratio (LSR) for piled rafts with all tips in clay.

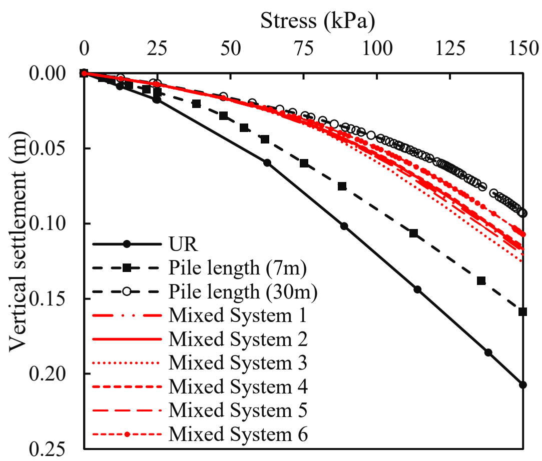

Figure 8. Relationship between stress and vertical settlement for UR, PR, and the combined foundation systems.

Table 4. Load sharing ratios as a ratio of total applied load.

	Pile loads (%)	End bearing (%)	Skin Friction (%)
1	51.79	23.31	28.48
2	52.44	20.08	32.37
3	50.64	21.72	28.92
4	52.10	20.05	32.05
5	52.37	20.46	31.92
6	53.33	14.97	38.35

5 CONCLUSIONS

Due to the potential for unacceptable settlements resulting from the utilization of un-piled rafts, this research compares three solutions of piled rafts: those with all pile tips in sand, those with all pile tips in clay, and a mixed system with some pile tips in sand and some in clay. Based on the study, the following remarks can be drawn:

- Friction piles were highly effective in decreasing settlement in such a challenging soil profile due to increased frictional resistance and bigger pressure bulbs.
- The combined system reduced settlement remarkably compared to using end-bearing piles alone. The system of higher pile numbers was the most efficient choice, offering nearly 90% of the friction piles system benefits while being economically advantageous.

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